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Physics of Systems Containing Neutron Stars

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Interim Report for 1994

This grant deals with several topics related to the dynamics of systems containing a compact object. Most of our research in 1994 dealt with systems containing Neutron Stars (NSs), but we also addressed systems containing a Black Hole (BH) or a White Dwarf (WD) in situations relevant to NS systems. Among the systems were isolated regular pulsars, Millisecond Pulsars (MSPs) that are either Single (SMPs) or in a binary (BMPs), Low Mass X-Ray Binaries (LMXBs) and Cataclysmic Variables (CVs).We also dealt with one aspect of NS structure, namely NS superfluidity.

A large fraction of our research dealt with irradiation-driven winds from companions. These winds turned out to be of some importance in the evolution of LMXBs and MSPs, be they SMPs or BMPs. While their role during LMXB evolution (i.e. during the accretion phase) is not yet clear, they may play an important role in turning BMPs into SMPs and also in bringing about the formation of planets around MSPs.

We concentrated on the following four problems:

The Windy Pulsar B1957+20 and its Evolution

In PSR B1957+20, the observed orbital period $\dot{\mathcal{P}}$ seems to change over timescales $\mathcal{T}$ of order $10^7 - 10^8$ yrs (Arzoumanian et al., 1994). If ξ is the angular momentum per unit mass for the binary and if the total gravitational potential is Φ, one can then show that for a small companion mass and for a small deviation from ordinary point-mass gravity, the change in total energy δE can be written as

$$\delta E = \epsilon_o \delta m - F\frac{\delta \mathcal{P}}{\mathcal{P}} + H\frac{\delta \xi}{\xi}, \tag{1}$$

where H is a constant, ϵ_o measures the excess specific energy in the wind and where, if the part of Φ that represents deviation from point masses is roughly a power law in a, $F \sim \mathcal{O}(m\Phi) = \mathcal{O}(m{v_{\rm orb}}^2)$. It follows from Eq. (1) that the corresponding change in orbital velocity of the binary over the above timescale involves a rate of energy change (lost or gained) of $\sim m v_{\rm orb}\dot{v}_{\rm orb} \sim \frac{GmM_{\rm NS}}{aT} \sim 10^{31} - 10^{32}$ erg/sec. If a wind is the broker for these energy exchanges (note that the Roche lobe [RL] surface in B1957+20 intercepts 6×10^{32} erg/sec from the pulsar), then $\dot{m} \sim 10^{16} - 10^{17}$ g/sec (since ${v_{\rm orb}}^2 \sim 10^{15}{\rm cm}^2/{\rm sec}^2$).

By combining self-consistently the idea of magnetic activity on the companion of B1957+20 (Applegate 1992) with the idea of the intense irradiation-activated mass loss, we were able to put together a scenario for the system that seems to be able to account for many features of B1957+20 (Applegate and Shaham 1994). In our scenario, magnetic activity directs the wind to leave the surface on field lines essentially out to the eclipse shock front. As a result, the companion spin is being magnetically breaked continuously. Tidal torques from the NS act to restore corotation and deposit entropy in the companion via tidal friction. This heat is sufficient to support the companion at its bloated configuration as well as to power its "dark" side luminosity in steady state, thus making the companion of B1957+20 the *first discovered tidally-powered star.*

From the above we can find when the evaporation in B1957+20 will be expected to really take off to very high mass-flow rates. First we notice that if the companion continues to fill the same fraction of its RL, then further evolution will cause, for some companion mass and at the present pulsar luminosity, the surface temperature to exceed the escape temperature. It is easy to find what that mass is: $\sim 40 M_{\oplus} a_p^{\frac{3}{4}}$, with a_p the orbital separation in units of the present one. It is easy to speculate, by analogy with Jupiter, that magnetic activity will still go on at that stage so that the companion will clearly maintain a fixed ratio with its RL. If it does not, we would simply have to wait for a lower mass to have the onset of intense evaporation. Once it has begun, however, the companion will evaporate completely because the illumination will provide super-escape thermal velocities throughout the whole process.

Wind "Echoes" in Tight Binaries

Several of the Soft X-Ray Transients (SXTs) from BH candidates were seen to be followed by secondary outbursts. A good example is Nova Persei, GRO J0422+32, that erupted in August of 1992 and by the end of 1993 had four secondary outbursts; the earlier ones were seen by BATSE and ASCA, some of these and the later ones were looked for and seen in the optical. The overall decay of the x-ray luminosity was typical: an almost perfect exponential decay with an e-folding time of order of a month, interrupted by the secondary bursts at roughly 4 month intervals. The optical bursts were less clear in their luminosity trend even though they did keep the inter-burst intervals and roughly coincided with the x-ray maxima when x-ray data was taken; however, in all bursts except, possibly, for the last one (of Dec '93), the optical luminosity may have been but a small fraction of the bolometric luminosity.

In modeling the SXT phenomenon one may want to separate the main burst from the secondary ones. Chen et al. (1993) pointed out that the latter might reflect some response of the system to the main burst. Following the first two secondary bursts, we (Augusteijn et al. 1993) suggested a simple model for the whole pattern of secondary bursts in terms of successive wind "echoes" of the main burst, which was able to predict correctly the times of the last two secondary bursts and the bolometric luminosity of the first of those (it was not possible to look at Nova Persei with a sensitive-enough x-ray satellite during the last secondary burst). It is in the framework of this model that we continued the theoretical research on wind "echoes".

In the model, we assumed that the centrally emitted x-rays are able to illuminate the companion through scatterings in a large corona, without having to worry about obscurations in the disk itself or in an inner corona. As the main burst occurs, it induces a burst of extra mass flow from the companion. This extra mass goes first into an orbit which is not too different from that of the companion, because the ratio of companion-to-BH masses is quite low. It takes several months for the material to drift into the inner disk, where x-ray emission occurs, and several days to drift through that region into the BH. The new burst of x-ray emission has less total energy than the main burst, but it nevertheless lifts a new burst of mass flow from the companion, that begins its way again into the BH to produce the next x-ray burst. All of the above assumptions guarantee that the secondary burst pattern comes about by simple linear response in the system with constant parameters.

As we predicted, J0422+32 has now gone back into its quiescent state. The optical data collected during the "echoes" do suggest that the disk is getting cooler as the overall intensity (hence $\dot{m}$?) drops, since the optical luminosity does not seem to drop from one "echo" to the other as fast as the X-rays did during the first "echoes" (when X-Rays were still visible). A crucial part of the understanding of the system (and the several others that seem to have been detected before and since Nova Persei) will be in modeling the "echo" to "echo" variations in luminosities of the various energy bands, while separating contributions from reprocessing of radiation in higher energy bands from direct disk luminosity, and in modelling the corona. Most recent calculations (Murray et al., 1994) indeed show that multiply-scattered radiation does act to partially offset the loss of direct radiation from the central source, predicted by earlier models to occur because of the inner corona; these multiple scatterings could well bring the radiation to the companion regardless of any close-to-the-plane shadowing effects.

In our phenomenological model (Augusteijn et al., 1993), the important physics was contained in the interburst time T and in the disk spread function: we assumed that after spending the time T at a distance of order of the companion distance matter goes through the inner disk on a timescale of order $\tilde{\beta}^{-1}$, while the flow stretches over a similar time scale (see, e.g., Bath et al., 1974). As we found from our fits to several bursts (notably GS200+25, 0620-003 and Nova Persei), $\tilde{\beta}^{-1} \ll \tilde{\gamma}^{-1}$, where γ^{-1} is the main burst decay time; hence the detailed shape of the spread function is, actually, not very critical for this picture.

In the original suggestion we did not comment on why the decay of the main burst was so clearly exponential, as that did not have anything to do with the echoes. We have now begun to look into this question.

Over the years, there have been two general frameworks in which the main burst was modeled: either as an inner disk instability (Tuchman et al., 1990) or as a companion mass transfer instability due to accumulation of excess entropy in the companion during the quiescent state (Hameury et al., 1986). The good fits that we have obtained for SXTs with our simple linear model described above are actually suggestive that the second of these options is the right one. One should understand how the exponential decay of the main burst comes about, assuming the latter is, indeed, due to a mass flow instability.

It is interesting that the e-folding time for the exponential decay of the main burst is of the same order ($\sim$ 1 month) as the interburst interval ($\sim$ 4 months). If the interburst interval represents, indeed, the time it takes matter to get from the L1 point down to the BH, it seems natural to interpret the e-folding time as due to matter motions inside the RL of the BH as well. We argue, quite generally, that in a stably accreting system, matter torques (coming from the mass flow stream and the disk, say) control the stability of the steady-state value of $\dot{m}$. Thus, if $\dot{m}$ drops suddenly, the change in tidal torques due to the new flow parameters will be such as to torque the binary into getting closer, so as to make the companion fill its RL a little more. Inversely, when a sudden rise in $\dot{m}$ occurs, the extra flow will change the tidal torques so as to make the binary expand slightly and make the companion move further from RL contact. During a transient event, the excess mass flow rate, $\dot{m}_e$, will therefore depend on the excess torque, hence (while excess matter still accumulates in the BH RL) on the total accumulation of the excess mass flow, $\int_0^t \dot{m}_e dt$ (we assume that the event begins at $t = 0$). This reasoning leads to an equation of the type

$$\dot{m}_e(t) \propto (-) \int_0^t \dot{m}_e(\tau) d\tau, \qquad (2)$$

hence the exponential behaviour.

We are now working to find Eq. (2) in simulations of the flow during non-steady-state situations.

Post Nova X-ray Emission in CVs

ROSAT observations of Nova Mus '83 (GQ Mus) showed some ten years of strong soft x-ray emission (Ogelman et al., 1993; x-rays seem to have turned off only recently). The spectral characteristics, as well as the Eddington-magnitude luminosity, were quite reminiscent of the LMC sources CAL 93, CAL 87 and RXJ 0527.8-6954, which are thought (van den Heuvel et al., 1992) to contain WDs on which nuclear burning of accreted matter occurs. Stable nuclear burning of this type was found to occur for mass accretion rates between $\sim 10^{-7}$ and $4 \times 10^{-7} M_{\odot} yr^{-1}$, which can be driven by either GR or Magnetic Breaking (MB) off $1.4 - 2.2 M_{\odot}$ companions. The orbital periods in question here being 1.04 and 0.44 days respectively for CAL 83 and CAL 87, this constitutes a consistent picture for these sources.

In spite of the similarities, GQ Mus could not possibly fit into the above picture, because its 85.5 min orbital period implies a $\sim .1 M_{\odot}$ companion (if the companion is to be close to filling its RL). We suggest that a decade-long episode of "self-excited" mass accretion could have taken place here. While the feedback factor here is, apriori, around 10^3 less than it would be were the compact object an accreting NS and were the x-ray luminosity due to free fall energy, it is only a factor of ~ 30 smaller if the x-rays are produced by nuclear burning of accreted material.

There is some evidence that accretion was present in the system while the x-rays were on. Optical observations reveal (Diaz and Steiner 1990) emission-line velocities and a light curve that is consistent with an AM type binary, whose companion is illuminated by the WD. For a companion radius R and surface temperature T, R^2T is constrained by these observations to be around $6 \times 10^{24}\ cm^2K$, yielding a surface illumination of $4.5 \times 10^{35} {R_{10}}^{-6} erg/sec$, with $R_{10} = \frac{R}{10^{10}cm}$ (for a main sequence companion of $.16M_\odot$, ${R_{10}}^6 \sim 2$). From the limit on the solid angle by which the WD sees the companion, the WD luminosity can be placed at $> 3 \times 10^{37} erg/sec$, thus confirming the x-ray estimates (which are always somewhat uncertain because of the high extinction factors at these wavelengths). We have modeled the Diaz and Steiner light curves in more detail and found them consistent with a RL-filling companion that is strongly illuminated by the WD but shadowed by an AM Her type stream of mass flow from the L1 point.

If bootstrapping really happens in the post Nova GQ MUs, the efficiency of illumination-to-mass-flow conversion is to be similar to that needed to explain BMP B1957+20, another source with very high such efficiency. We are now exploring the possibilities for this particular system and for post Nova CVs in general.

Dynamics of Pinned Superfluids in Neutron Stars

Neutral superfluids can rotate if they contain quantized vortices of density

$$n_N = \frac{2\Omega}{\kappa} \sim 7 \cdot 10^6 \left(\frac{\Omega}{10^3 sec^{-1}} \right) cm^{-2} \ , \tag{3}$$

where κ is the quantum of vorticity, $\kappa \sim 3 \cdot 10^{-4} cm^2 sec^{-1}$. Charged superfluids (i.e. superconductors) can carry a magnetic field if they contain quantized magnetic vortices of density

$$n_C = \frac{B}{\Phi_\circ} \sim 5 \cdot 10^{15} \left(\frac{B}{10^9 G} \right) cm^{-2} \ , \tag{4}$$

where $\Phi_\circ \sim 2 \cdot 10^{-7}\ Gcm^2$ is the flux quantum.

Quantum fluids form in NS interiors by Cooper pairing of "dressed" crust or core neutrons or "dressed" core protons (Sauls 1989). Cooper-pair binding energies are a few hundred keV and depend on the local density and composition of matter. Cooper pairing is broken in the vortex cores, which have to contain *normal* fluid; therefore vortices will form locally where binding is weakest to begin with. This will create an affinity (pinning) of vortices to certain microscopic locales in the NS such as crustal nuclei, spaces between nuclei, or cores of vortices of the other kind (in the NS core). Pinning forces are of order of the binding energy gradients, $\sim 10^{17} - 10^{18} dyne/cm/vortex$.

The global rotation of a superfluid is determined by the *locations* of its vortex lines. These, in turn, move downstream unless a force acts on their normal cores; in this case they acquire an extra velocity component *perpendicular* to the force, of a magnitude proportional to it. When embedded in a normal fluid that rotates slower than the vortex density implies [by Eq. (3)], tangential friction between the normal fluid and the vortex cores sends the vortices *outwards* and the vortex lattice dilutes itself for the lower rotation rate. However, when pinned to centers corotating with the normal fluid, the vortices will not move unless the Magnus force overcomes the pinning. In general, friction will produce a *microscopic* displacement of the vortex radially outwards, into the pinning energy gradient region. The resulting *radially inwards* pinning force will introduce a backward tangential velocity for the vortex , thus forcing the vortex to move with the (lesser) speed of the pinning centers, in spite of the higher vortex density. The superfluid will only be able to slow down if the Magnus force (proprtional to the velocity difference between the vortex core and the superfluid) causes unpinning or if it can break the lattice and carry the pinning sites with it.

Sudden unpinning events have long been considered good candidates for causing spin up "glitches" in pulsars (see, e.g., Alpar and Pines 1989): the sudden slowdown of the superfluid is countered by the observed sudden spinup of the crust. One of the mysteries of this scenario is how a collective unpinning event comes about. We started with a single vortex, unpinning under the appropriate maximal Magnus force. As it is spiralling out, a superposition of the motion downstream and the radial component introduced by friction, it collides with other pinned vortices which are also on the verge of being unpinned. The extra (small) velocity that it induces on them during this close encounter can bring about their final unpinning and so, in an avalanche, a bunch of unpinned vortices is formed. Another mystery has to do with the distance which a bunch travels until repinned, if repinned. To repin, a vortex must lose its energy to something. Back-of-the-envelope calculations show that the energy of an unpinned vortex under typical conditions fits right into the energy gap between acoustical and optical lattice phonons and it would not be able to lose its energy to the lattice. We consider energy loss of the vortex to friction as the main repinning mechanism. Both the travel distance and the initial bunching determine the observed rise time and magnitude of a "glitch".

The basic equation governing the motion of a single vortex line, in the rigid vortex approximation, is

$$\rho_s[(\mathbf{v}_s - \mathbf{v}_L) \times \mathbf{k}] - \eta(\mathbf{v}_L - \mathbf{v}_n) + \eta'[(\mathbf{v}_L - \mathbf{v}_n) \times \mathbf{k}] + \mathbf{f}_P = \mathbf{0} \ , \tag{5}$$

where ρ_s is the superfluid density, η and η' the longitudinal and transversal viscosity coefficients, $\mathbf{k}$ the vortex vorticity (of magnitude κ), $\mathbf{v}_s$ the local superfluid velocity, $\mathbf{v}_L$ the velocity of the vortex line, $\mathbf{v}_n$ the velocity of the normal component and $\mathbf{f}_P$ the pinning force. All bold-faced quantities are 2-D vectors in the plane perpendicular to the rotation axis except for $\mathbf{k}$, which is parallel to that axis. In the above equation, the first term is the Magnus force and the next two terms represent the longitudinal and transverse frictional forces due to the interaction with the electrons and the crustal phonons in the crust. The pinning force $\mathbf{f}_P$ is a function of the relative vector between the vortex line and the pinning site: if $\mathbf{r}$ is the location of the vortex and $\mathbf{R}_i$ the location of the $i-th$ pinning site (assumed here to really be a pinning *line*), then $\mathbf{f}_P = \mathbf{f}_P(\mathbf{r} - \mathbf{R}_i)$.

A second set of equations describes the motion of the pinning sites. These are acted upon by the ordinary forces in the NS crust as well as by the pinning force due to the vortex and can be simply represented as a coupled set of harmonic oscillator equations or, for more simplicity, by a single harmonic oscillator equation with some angular frequency $\omega_\circ$.

We are now assuming that $\mathbf{v}_n$ is given and that, as a first approximation, so is $\mathbf{v}_L$. At a later stage we shall put in by hand some "glitch" function to mimic self consistently the superfluid rotation based on the picture we shall have from the behaviour of a single vortex. The binding energy will be first modeled as some Fermi function which vanishes at the center of the pinning site and rises to the value of $\epsilon_{C,max} - \epsilon_{C,min}$, the maximum variance of Cooper pair binding energy per particle values ϵ_C, over a distance of order $10fm$ (the force is the gradient of this function). We shall then attempt to calculate it more accurately from the most recent local equations-of-state around crustal nuclei. As we follow numerically the paths of a vortex just unpinned, we shall calculate the cross section for unpinning other vortices to obtain the rate at which the bunch is formed, and later watch the rate of repinning once we introduce the model for the change in superfluid rotation rate. We shall do all the calculations for various sets of reasonable friction and pinning parameters.

Unpinning occurs when the energy density of relative motion grows to a sufficiently high value, i.e. to roughly $\epsilon_{C,max} - \epsilon_{C,min}$ in the region. Lattice breaking occurs under similar conditions involving the lattice. This limiting energy density may well exceed in some regions the value of $\epsilon_{C,max}$, the binding energy per particle at the pinning site. In this case, it may be energetically favorable to form a new vortex of the opposite (negative) vorticity on a neighboring pinning site and decrease the positive vorticity in this way rather than move (the positive) vortices out. Vortex formation is a local process. Since a mismatch exists between the motions of the superfluid and the (slower) normal component, the latter is seen locally to rotate in the *reverse* direction; so, with the availability of energy, a negative vortex is sure to form if vortices can at all form in the region.

If negative vortices do form, many ideas regarding NS crustal superfluidity will have to be reexamined. These include unpinning events as sources of "glitches", and magnetic field decay during crustal "continental drift" induced by pinned vortices breaking the lattice and moving outward carrying the lattice with them (Ruderman 1991). We are now trying to assess the possibility of forming negative vorticity in NS crusts in detail.

This project is, probably, the most complex part of this work. To determine the possibility for negative vortex formation we need firstly good estimates for Cooper pair binding energies in the local environment of a crustal nucleus. While these do exist (and suggest favorable conditions at least in some parts of the crust), they may not be reliable enough to detemine whether the energetics favors negative vortex formation. It is hard to see how to do better calculations on this question, because the main uncertainty are the many body calculations, which were not tested in the laboratory for these systems. Secondly, we need to determine how these vortices form even if the energetics *is* favorable, because vortices can only form in regions bordering normal neutron fluid.

One way to form them is this: an existing vortex may stretch and elongate in a non-pinned segment, first up the axis to be equivalent to a negative vortex and then outwards and down the axis again. This will effectively create a negative vortex next to the pinned existing one, as well as another positive vortex further away. One needs to create two normal core lines here, not one (of course they should end up pinned), so the energetics will be different, but once we can prevent repinning until the full new lines are in place, it will be a viable process. Alternatively, repinning may take place continuously and each generation will put out additional loops; this will take more than two new normal cores per existing vortex but we should remember that it is only the instantenous energetics that we need to worry about: there is enough energy on the rotational energy reservoir to form many vortex cores per each existing one.

We can make some phenomenological statements here as well. Consider, for example, a MSP that was spun up from a low spin while its interior was already at temperatures much below the superfluid transition. It is going to need to fill itself up with a number of neutron vortices that far exceeds the number it started with, to accommodate to the new spin rate, or else its superfluid neutrons are going to continue to rotate at their old rotation rate. Any way which the superfluid can find to form these vortices will also be a way for it to form negative vortices once slowdown begins (provided the enrgetics is right). Thus, either MSPs do not have enough neutron vortices to have any influence on the magnetic field or they do, in which case they may again not have any effect on B because negative vorticity will form.

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